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High-performance geopolymer concrete: enhancing durability with GGBS and fiber reinforcements

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ABSTRACT

This research assesses the mechanical and durability performance of geopolymer concrete (GPC) using fly ash, GGBS, and fiber reinforcements. 23 various GPC mixes were tested, each with varying amounts of GGBS (0–20%), steel fibers (0–2%), nylon fibers (0–2%), and glass fibers (0–2%). The best mix with 20% GGBS and 2% steel fibers produced the maximum compressive strength of 55.6 MPa. Sorptivity was lowest at 3.70×10^{-5} $m/s^{1/2}$, reflecting minimum water absorption. The lowest RCPT value of 383 Coulombs categorized the mix as low-permeability concrete, providing excellent resistance to chloride ion penetration. Acid resistance tests registered negligible weight loss of 3.06%, while sulfate attack tests demonstrated minimum loss of strength of 3.60%. The optimized mix also demonstrated maximum resistance to saltwater exposure and reduced deterioration in aggressive environments. The research attests that geopolymer concrete with steel fibers and GGBS possesses enhanced mechanical strength and durability, making it a sustainable and high-performance material compared to ordinary concrete. These results demonstrate the potential of GPC in structural applications subjected to severe environmental conditions, advancing eco-friendly and durable construction materials.

Keywords: Flyash; GGBS; Steel Fibre; Nylon Fibre; Glass Fibre.

1. INTRODUCTION

Geopolymer concrete is a green substitute for conventional Portland cement concrete using industrial waste materials like fly ash and GGBS in order to sustain the environment as well as reducing carbon emissions [1]. Geopolymer concrete mixtures are usually composed of 50–80% fly ash and 20–50% GGBS as a binding material, which significantly reduces embodied carbon content compared to conventional mainstream cement [2].

The inclusion of other fibers, such as steel, nylon, and glass, improves the mechanical and durability properties of the material. Steel fibers, added at a volume ratio of 0.5–2.0%, significantly improve the durability and mechanical properties of geopolymer concrete [3]. Research indicates that steel fiber-reinforced geopolymer concrete can possess compressive strengths of 40–80 MPa, depending on the mix ratio, and exhibits marvelous resistance to impact and cracking [4]. Additionally, the addition of steel fibers can result in a decrease in sorptivity, a key parameter of permeability, by up to 40%, thus increasing the resistance of the concrete to water penetration and adverse environmental conditions. All these developments make steel fiber-reinforced geopolymer concrete highly apt for use in infrastructure projects where high durability is a requirement [2, 5].

Nylon fibers improve the tensile strength, crack resistance of geopolymer concrete. The incorporation of nylon fibers in the proper proportion of 0.1–0.3% volume, along with fly ash (50–80%) and GGBS (20–50%), can result in a gain in compressive strength up to 15%, flexural strength of 10–20%, and tensile strength of 20–30% [3, 6]. The mixture significantly improves the overall durability of the concrete, and it is particularly beneficial for use in pavements, where performance and sustainability are paramount [6].

The addition of glass fibers to geopolymer concrete in the range of 0.5–1.5% by volume increases its mechanical strength and durability. Use of hybrid glass fibers provides compressive strengths of 45 to 85 MPa, improves tensile strengths by 15 to 25%, and improves the modulus of elasticity by 10 to 20% [7]. Glass fibers also reduce water absorption by up to 35% and reduce sorptivity and improve water penetration resistance of the concrete and wear. These improvements significantly contribute to the long-term durability of geopolymer concrete [8].

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The addition of fibers and GGBS significantly improves the compressive, tensile, and flexural strengths of geopolymer concrete. Partial substitution of 50% of the fly ash by GGBS and inclusion of steel fibers in 1.0–2.0% by volume volume, for instance, increases compressive strength up to 100%, i.e., 40 MPa to 80 MPa, and tensile strength by 58%, i.e., from 3.8 MPa to 6.0 MPa [5, 9]. Steel fibers are especially efficient in promoting flexural toughness, with a 30–50% rise in flexural strength, reducing the susceptibility of geopolymer concrete to cracking and mechanical stresses [10]. Glass fibers also contribute towards an increase in the energy-absorbing capacity by 20–35% and reducing brittleness, and thus, the concrete can be used in high-impact applications such as airport runways and industrial flooring [11].

Use of GGBS and Fly Ash in geopolymer concrete has two aims: environmental sustainability and material durability improvement. GGBS enhances long-term strength development, with the maximum strength development being up to 20% in the long term, and enhances sulfate and chloride attack resistance up to 60%, making the concrete more durable under aggressive environments [9, 12]. Fly ash helps to make the product more sustainable by eliminating the dependency on the use of traditional cement and industrial by-product recycling. The blending of the above materials with fibers leads to a denser microstructure, lowering permeability and improving the overall mechanical behavior and durability [13].

The addition of GGBS and steel and glass fibers to geopolymer concrete forms a denser and more uniform matrix. This is due to the increased pozzolanic activity and pore filling, which enhance the mechanical strength and durability of concrete [6, 10, 14]. Substitution of 30–50% GGBS for fly ash increases compressive strength by as much as 40%, and the inclusion of 1.0–2.0% volume steel fibers increases tensile and flexural strengths by 50–70% and 30–50%, respectively. Steel fibers even enhance interfacial bonding with the geopolymer matrix, resulting in increased resistance to cracking and impact strength [15]. Microstructural observation under SEM shows a dense and cohesive matrix with few pores, which decreases permeability by as much as 35%, critical to the enhanced performance of fiber-reinforced geopolymer concrete [16].

The incorporation of GGBS and fibers greatly increases the hardness of geopolymer concrete, rendering it very resistant to environmental attacks such as freeze-thaw cycles and sulfate exposure [17]. Experiments confirm that sulfate resistance is enhanced by 60%, while freeze-thaw durability shows a 50% improvement owing to the development of a compact microstructure along with the presence of calcium silicate hydrate (C–S–H) and aluminosilicate gels [10, 18]. Geopolymer concrete presents a green option over regular concrete, inducing a carbon footprint reduction of up to 80% when compared with ordinary Portland cement. Utilization of industrial waste products, including fly ash and GGBS, not only diminishes wastes but also aids in the environmental advantages of the material [14, 19].

Exposure of alkali-activated materials to sulfuric acid typically results in mass loss, microstructural degradation, and strength reduction. However, the extent of deterioration strongly depends on the binder chemistry, gel structure, and curing conditions. In our study, we observed a range of responses across compositions, with slag-rich systems generally showing higher strength retention than fly ash-rich ones after 28 days of acid immersion [20]. This trend can be attributed to differences in the predominant gel phases formed. Slag-based binders form C–A–S–H gel, which provides a denser microstructure and contributes to early strength development. However, C–A–S–H is more vulnerable to acid-induced decalcification, leading to structural destabilization over time. Conversely, fly ash-based systems form N–A–S–H gel, which has higher chemical resistance due to its lower calcium content but may exhibit higher porosity, making it susceptible to acid ingress and mass loss [21]. Interestingly, some specimens showed minimal strength loss or even slight increases after acid exposure. This phenomenon may result from continued geopolymerization under sealed immersion conditions, where water ingress and elevated humidity promote further gel development—especially in systems with unreacted precursors. This “sealed curing” effect under immersion can temporarily improve mechanical performance, masking early-stage degradation [22].

The long-term implications of acid exposure include progressive leaching of calcium, aluminum, and silicon species, ultimately weakening the binder network. Thus, while short-term strength retention may appear favorable, especially in slag-rich systems, this should not be interpreted as chemical stability without concurrent mass loss and microstructural evaluation [23]. Our results align with these findings. Mass loss and surface erosion were more pronounced in fly ash-rich blends, despite their chemical resistance, likely due to physical degradation from acid penetration. Conversely, slag-rich mixes showed better mechanical stability but exhibited initial signs of gel decalcification upon SEM observation [24, 25].

The addition of fibers, particularly in large amounts, can adversely influence the workability of geopolymer concrete. Therefore, proper mix design and optimization are required to obtain a proper balance between workability and mechanical properties.

Limited understanding of long-term durability under aggressive conditions. While short-term durability results are promising, the long-term degradation mechanisms, especially under sustained exposure remain underexplored. There is no standardized approach to optimizing fly ash-to-GGBS ratios. Fiber type and volume. Excess fibre content particularly steel and glass negatively affects workability, making placement and compaction difficult. However, fiber dosage has a direct impact on toughness and durability. Fiber dispersion techniques, use of superplasticizers compatible with alkali-activated systems.

2. MATERIALS AND METHODS

Cementitious, aggregate, and fiber content are integral to the performance of concrete. OPC 33 Grade contains specific gravity of 3.15, particle size of less than 90 µm, and bulk density of 1285 kg/m^3 [26]. Fly ash and GGBS are supplementary cementitious materials that enhance the performance properties of concrete, and fly ash contains specific gravity of 2.45 and fineness of 315 m^2/kg, while GGBS contains specific gravity of 2.91 and fineness of 412 m^2/kg [27]. Chemical composition of the materials contributes significantly to their performance; for example, OPC contains 63.65% CaO and 22.65% SiO_2, while fly ash and GGBS exhibit higher SiO_2 content of 55.73% and 41.34%, respectively, which enhances durability and strength development. Physical and chemical characteristics of the cementitious materials are listed in Tables 1 and 2.

Aggregates make up the majority of concrete, with fine aggregate having a particle size of less than 2.36 mm, a specific gravity of 2.66, and a bulk density of 1541 kg/m^3 [28]. The most typical coarse aggregate size is 20 mm, with a specific gravity of 2.76 and a bulk density of 1645 kg/m^3. The workability and durability of concrete mixes are determined by their water absorption concentration, which is 0.5% for fine aggregate and 1% for coarse aggregate. The physical features of aggregates are shown in Table 3.

Table 1: Physical properties of cementitious materials.

PHYSICAL PROPERTIES	CEMENT OPC 33 GRADE	FLYASH	GGBS
Specific Gravity	3.15	2.45	2.91
Particle Size	< 90 µm	< 45 µm	< 45 µm
Bulk Density	1285 kg/m^3	1169 kg/m^3	1262 kg/m^3
Color	Grey Powder	Grey Powder	Off-White Powder
Fineness	364 m^2/kg	315 m^2/kg	412 m^2/kg

Table 2: Chemical properties of cementitious materials.

CHEMICAL PROPERTIES	CEMENT OPC 33 GRADE	FLYASH	GGBS
SiO_2	22.65%	55.73%	41.34%
Al_2O_3	5.87%	21.41%	13.34%
Fe_2O_3	5.10%	8.83%	2.12%
CaO	63.65%	2.56%	33.97%
MgO	1.86%	1.15%	7.23%
SO_3	< 3%	–	< 2%
LOI	1.51%	< 5%	–

Table 3: Physical aggregates.

PHYSICAL PROPERTIES	FINE AGGREGATE	COURSE AGGREGATE
Particle Size	< 2.36 mm	20 mm
Specific Gravity	2.66	2.76
Bulk Density	1541 kg/m^3	1645 kg/m^3
Fineness Modulus	2.4	3.1
Water Absorption	0.5%	1%

Table 4: Physical properties of fibres.

PHYSICAL PROPERTIES	STEEL FIBRES	NYLON FIBRES	GLASS FIBRES
Diameter	0.5 mm	25 µm	25 µm
Length	50 mm	50 mm	50 mm
Tensile Strength	1035 MPa	485 MPa	1768 MPa
Density	7830 kg/m^3	1150 kg/m^3	2548 kg/m^3

Fibers play a major role in enhancing the mechanical properties and durability of concrete. Steel fibers with a 0.5 mm diameter, 50 mm length, and 1035 MPa tensile strength enhance toughness and crack resistance [29, 30]. Nylon fibers with a 25 µm diameter, 485 MPa tensile strength, and 1150 kg/m^3 density also enhance crack resistance [25]. Glass fibers, with 25 µm diameter, possess the highest tensile strength of 1768 MPa and density of 2548 kg/m^3, hence enhancing impact resistance and minimizing brittleness [31]. Adding these various materials to concrete leads to a construction material that is strong, durable, and sustainable. Table 4 summarizes the physical properties of the fibers.

3. METHODOLOGY

The investigation includes a variety of concrete mix designs that are distinguished by different curing conditions, supplementary cementitious materials, and fiber reinforcements. M1 is regular concrete, which is adopted as a control group [32]. Mixes M2 to M6 employ GGBS as a complete or partial replacement of fly ash with ambient temperature curing. Similarly, mixes M7 to M11 employ the same replacement pattern but with high temperature of 60°C curing. Mixes M12 to M15 consist of steel fibers in the proportion range of 0.5% to 2% with 100% GGBS and room temperature curing, and mixes M16 to M19 work with nylon fibers in the same proportion range. Finally, mixes M20 to M23 replace nylon with glass fibers, also with the proportion range from 0.5% to 2%. The testing protocols were developed with reference to established standards to ensure consistency and reproducibility. The acid resistance test followed procedures adapted from ASTM C267. Specimens were immersed in a 5% sulfuric acid (H_2SO_4) solution at room temperature for a duration of 28 days. Prior to immersion, the specimens were oven-dried and their initial masses were recorded. During the exposure period, the solution was replaced weekly to maintain consistent concentration [33]. After 28 days, specimens were removed, rinsed with distilled water, dried, and weighed to assess mass loss as an indicator of degradation. Sulfate resistance was evaluated using a method aligned with ASTM C1012. Specimens were immersed in a 5% sodium sulfate (Na_2SO_4) solution at room temperature. The solution was refreshed weekly [34, 35]. Expansion and surface deterioration were monitored visually and through mass change measurements at regular intervals over a 28 days period [36]. To simulate salt exposure (e.g., deicing or marine environments), specimens were immersed in a 3.5% sodium chloride (NaCl) solution, consistent with seawater concentration. The test duration was 28 days, with weekly solution replacement. Post-exposure, specimens were rinsed and dried before assessing changes in mass, surface integrity, and visual signs of deterioration.

All mechanical and durability tests were conducted in triplicate to ensure reproducibility. Reported values represent the mean of three measurements, with standard deviations calculated and included in all relevant tables and figures. Error bars in graphical data represent ± one standard deviation from the mean. This statistical treatment enables assessment of data variability and enhances the confidence in comparative analyses across different mix designs and curing conditions. This systematic arrangement allows the investigation of the impact related to supplementary materials, curing conditions, and different fibers on the properties of concrete. The morality of the mix is 10, $NaOH/Na_2SiO_3$ and used in this research is 2.5. Table 5 reports the mix proposals for the different formulations.

4. RESULTS AND DISCUSSION

4.1. Saturated water absorption test results

The results of water absorption tests of different concrete mixes after 28, 56, and 90 days are presented in the table. Observations indicate the differences in water absorption due to different curing modes, fly ash-to-GGBS ratio, and the addition of steel, nylon, and glass fibers.

4.1.1. Effect of fly ash and GGBS content

Mix M1 (Normal Concrete) recorded maximum values of water absorption (5.72% at 28 days and 5.09% at 56 days). When 100% GGBS was incorporated (M2), a significant reduction in water absorption was observed

Table 5: Mix proposition of various mix.

MIX	CURING MODE	FLY ASH	GGBS	STEEL FIBRES	NYLON FIBRES	GLASS FIBRES
		(%)	(%)	(%)	(%)	(%)
M1	Conventional Concrete					
M2	Curing at Room Temperature	0	100	–	–	–
M3		5	95	–	–	–
M4		10	90	–	–	–
M5		15	85	–	–	–
M6		20	80	–	–	–
M7	Curing at 60°C Temperature	0	100	–	–	–
M8		5	95	–	–	–
M9		10	90	–	–	–
M10		15	85	–	–	–
M11		20	80	–	–	–
M12	Curing at Room Temperature	0	100	0.5	–	–
M13		0	100	1	–	–
M14		0	100	1.5	–	–
M15		0	100	2	–	–
M16		0	100	–	0.5	–
M17		0	100	–	1	–
M18		0	100	–	1.5	–
M19		0	100	–	2	–
M20		0	100	–	–	0.5
M21		0	100	–	–	1
M22		0	100	–	–	1.5
M23		0	100	–	–	2

(4.86% at 28 days, 4.32% at 56 days, and 3.84% at 90 days). As the percentage of fly ash in mixes M3 to M6 increased, water absorption increased gradually. Maximum absorption was observed in M6 (20% fly ash, 80% GGBS), which indicates that high fly ash content can reduce compactness and enhance permeability.

4.1.2. Effect of curing temperature

For thermally cured geopolymer concrete at 60°C (M7 to M11), the water absorption levels were invariably lower than that under room temperature curing (M2 to M6). M2 (room temperature) exhibited a 90-day absorption of 3.84%, whereas M7 (curing at 60°C) exhibited higher absorption (4.03%). But a general trend of lower water absorption with incorporation of fly ash was also evident. The minimum absorption for this series was indicated by M11 (4.79% at 90 days), supporting the fact that polymerization is higher and porosity is lower through thermal curing.

4.1.3. Effect of steel fibers

The use of steel fibers (M12 to M15) led to lower water absorption. The 2% steel fiber combination (M15) witnessed the decrease in water absorption to 4.70% at 28 days, 4.18% at 56 days, and 3.72% at 90 days as compared to M2. This verifies that steel fibers enhance compaction and reduce voids, thus resulting in lower permeability.

4.1.4. Effect of nylon fibers

Nylon fiber-reinforced composites (M16 to M19) exhibited the same trend with a decrease in water absorption due to the inclusion of fiber. The lowest absorption (4.42% at 28 days and 3.49% at 90 days) was shown by the 1.5% nylon fiber (M18) composition, and this suggests the inclusion of nylon fibers helps decrease the microcracks and matrix integrity.

4.1.5. Effect of glass fibers

Glass fiber blends (M20 to M23) were less absorbent with water. M22 consisting of 1.5% glass fibers was 3.53% absorption at 90 days, which was lower than the steel fiber-reinforced blend M15. Glass fibers can increase internal bonding and reduce microcracks.

4.1.6. Comparative analysis

- The lowest water absorption after 90 days was in M18 (3.49%), which indicates that 1.5% nylon fibers have a significant role in reducing permeability.
- The highest absorption was in M6 (4.56% at 90 days), which demonstrates the effect of high fly ash on permeability.
- Curing is important; geopolymer concrete cured at high temperatures had reduced water absorption, improving durability.

4.1.7. Conclusion

The study indicates that GGBS geopolymer concrete absorbs less water compared to regular concrete. Resistance to water absorption is also improved through the addition of fibers (steel, nylon, and glass), of which nylon fiber reduces the most. High-temperature curing is also involved in the reduction of permeability, which makes geopolymer concrete a potential replacement in long-term application in building. Figure 1 is the result of water absorption testing.

4.2. Acid resistance performance

Acid resistance of different mixes was evaluated in percentage weight loss and strength loss after immersion in hydrochloric acid (HCl) for 28, 56, and 90 days. Mix composition and curing conditions are found to have a significant influence on acid resistance.

4.2.1. Effect of fly ash and GGBS proportions

- Mixtures M2 to M6 and M7 to M11 consisted of different combinations of fly ash and GGBS subjected to two curing conditions (ambient temperature and 60°C).
- Percentage loss in weight and percentage loss in strength decreased when the percentage replacement of fly ash increased to 20%.
- For instance, Mix M6 (20% fly ash, 80% GGBS) saw a reduction in weight loss from 7.53% at 28 days to 4.86% at 90 days, which was lower than M1 (normal concrete) that recorded 7.49% and 4.83% weight loss for the same period.
- 60°C Curing (Mixes M7–M11) also promoted resistance, with reduced weight and strength loss than those cured at room temperature.

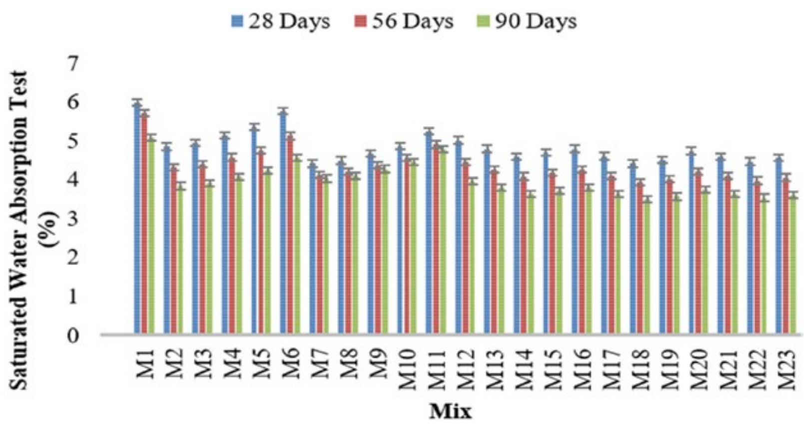

Figure 1: Water absorption test results.

4.2.2. Effect of steel fibers

- Steel fibers incorporated into mixes M12 to M15 greatly improved acid resistance.
- Higher proportion of steel fibers led to better performance, Mix M15 containing 2% steel fibers having least weight loss (3.38% at 28 days) and strength loss (3.86% at 28 days) than the control mix M1.
- This indicates steel fibers improved the matrix toughness and resistance to cracking when exposed to acid.

4.2.3. Effect of nylon fibers

- Mixed M16 to M19 contained nylon fibers, and their behavior followed that of steel fibers.
- Increased fiber content of nylon resulted in lower weight and strength loss, Mix M19 (2% nylon fibers) showing a weight loss of 7.47% at 28 days whereas Mix M12 (0.5% steel fiber) showed a weight loss of 5.03%.
- Nylon fibers enhanced crack resistance but were somewhat inferior to steel fibers.

4.2.4. Effect of glass fibers

- Mixtures M20 to M23 had glass fibers, which were more resistant to acid than regular concrete but less resistant to acid than steel and nylon fibers.
- 2% glass fibers in M23 had 5.07% loss in strength and 4.44% loss in weight after 28 days, once again a much better figure than the M1 (7.49% loss in weight, 8.56% loss in strength).

4.2.5. Influence of curing conditions

- 60°C curing showed a remarkable increase in acid resistance (Mixes M7 to M11) over room-temperature curing (Mixes M2 to M6).
- For example, M11 (20 fly ash, 80 GGBS, 60°C curing) recorded lower weight loss (7.23% after 28 days) than M6 (7.53%).
- This is due to rapid geopolymerization at high temperatures, which creates a denser and more solid matrix.

4.2.6. Comparative performance analysis

- Traditional concrete (M1) had the highest loss in weight and strength, reflecting poor acid resistance.
- The most effective blend in weight loss was M15 (2% steel fibers) and M19 (2% nylon fibers), while the most effective blend in strength retention was M15.
- Steel fiber mixes showed better resistance to acids, followed by nylon fibers, glass fibers, and fly ash-GGBS-based mixes.

4.2.7. Conclusion

- The incorporation of fly ash and GGBS enhanced acid resistance, with best performance at 20% replacement of fly ash.
- Steel and nylon fibers also added strength, 2% steel fibers offering maximum resistance.
- Increased curing temperature (60°C) enhanced performance by speeding up geopolymerization and the structure of the matrix. Figure 2 and 3 illustrates the percentage loss of weight and strength after acid attack.

4.3. RCPT

4.3.1. Influence of GGBS replacement on RCPT Values

The findings show a considerable decrease in RCPT values for geopolymer concrete in comparison to regular concrete. Mix M1 (Regular Concrete) contained the highest RCPT values of 3425, 2751, and 2209 at 28, 56, and 90 days, respectively. With replacement of fly ash by GGBS in geopolymer concrete, RCPT values were consistently upgraded. For curing at room temperature, M2 (100% GGBS) exhibited an RCPT value of 995 at 28 days, which decreased to 642 at 90 days. Analogously, by adding more GGBS content from 5% (M3) to 20% (M6) the durability exhibited a steady improvement. The same trend was noted in heat-cured specimens (M7–M11), in which M11 (20% GGBS) had the lowest RCPT values (1272, 1052, and 891 at 28, 56, and 90 days, respectively).

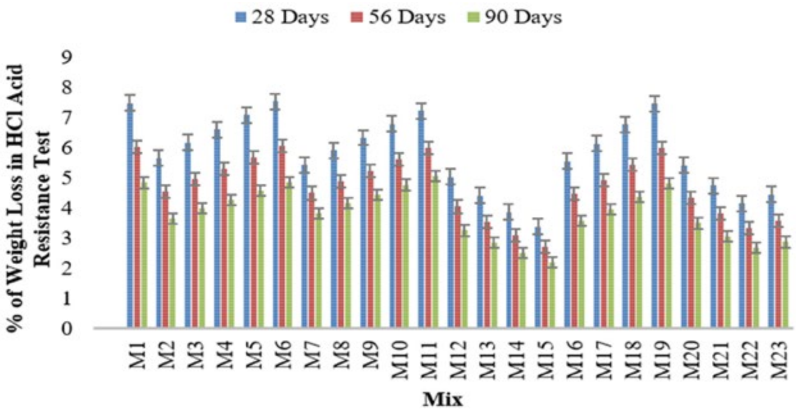

Figure 2: Percentage of weight loss after acid attack.

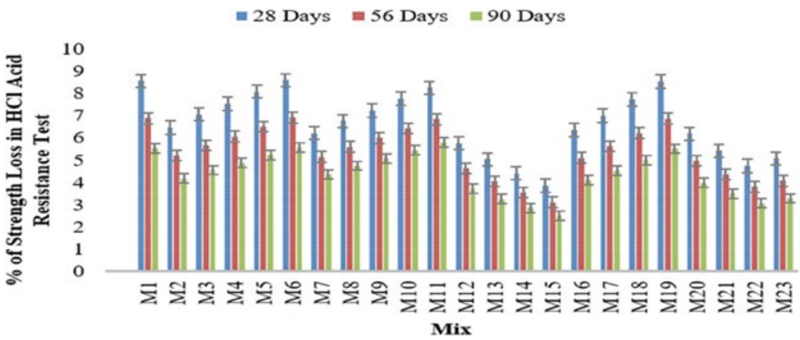

Figure 3: Percentage of strength loss after acid attack.

4.3.2. Impact of higher temperature curing

Curing temperature was of vital importance in minimizing chloride penetration. For mixtures of comparable composition, samples cured at 60°C (M7–M11) consistently recorded lower RCPT values than room temperature-cured specimens (M2–M6). For example, mix M6 (20% GGBS, room temperature) registered an RCPT of 1325 at 28 days, while its heat-cured equivalent M11 measured 1272, reflecting improved performance through accelerated polymerization and densification.

4.3.3. Effect of steel fibers on RCPT performance

Addition of steel fibers (M12–M15) decreased RCPT values further, and an increase in the fiber content resulted in a greater decrease. Mix M15 with 2% steel fibers had the lowest permeability (594 at 28 days, 477 at 56 days, and 383 at 90 days) and proved that steel fibers are very good for inhibiting chloride ingress.

4.3.4. Effect of nylon fibers on chloride resistance

Nylon fibers helped achieve better durability through the resistance of chloride penetration. Mix M19 (2% nylon fibers) had lowest RCPT values in the cases of nylon fiber mixes (1315, 1056, and 848 at 28, 56, and 90 days of ages, respectively). The good performance is ascribed to nylon fiber's crack-bridging action, thus reinforcing matrix stability.

4.3.5. Effect of glass fibers on RCPT

Adding glass fibers (M20–M23) exhibited a considerable decrease in RCPT values, but less than that of steel fibers. Mix M23 (2% glass fibers) recorded an RCPT value of 781 at 28 days, which decreased to 504 at 90 days, reflecting improved durability. Compared to steel fiber mixes, though, the improvement was relatively moderate.

4.3.6. Overall comparison and best-performing mix

Out of all the mixes, M15 (100% GGBS with 2% steel fibers) showed highest resistance to chloride penetration and lowest RCPT values at all curing ages. Heat-cured mixes also showed improved performance compared to room-temperature-cured mixes, verifying the beneficial effect of high temperature on geopolymerization.

4.3.7. Conclusion

- Geopolymer concrete performed greatly better than regular concrete in the resistance to chloride penetration.
- Higher GGBS content enhanced durability by lowering RCPT values.
- High temperature curing improved chloride resistance over ambient curing.
- Steel fibers were the most efficient in lowering RCPT values, followed by nylon and glass fibers.
- The optimum combination was M15 (100% GGBS with 2% steel fibers), which exhibited the lowest value of chloride permeability. Figure 4 displays the RCPT results.

4.4. Salt water resistance test

4.4.1. Weight loss analysis

The loss in weight of various mixes of concrete which are tested by the saltwater resistance test within 28, 56, and 90 days indicates durability.

- Traditional Concrete (M1) had the highest loss in weight, with 18.36% at 28 days, which decreased to 11.84% at 90 days.
- Geopolymer Concrete with GGBS (M2–M6, M7–M11) recorded much lower weight loss compared to normal concrete, reflecting greater resistance. Weight loss reduced with increasing fly ash percentage, with the lowest weight loss of 11.48% at 28 days being recorded by M6 (20% fly ash).
- Impact of Curing Temperature: Specimens cured at 60°C (M7–M11) gained a small amount of weight loss when compared to those cured at ambient temperature (M2-M6). M11 (20% fly ash) registered the minimum weight loss (11.02% at 28 days), showing the beneficial effect of high temperature curing.
- Influence of Fibres: Steel fibres (M12–M15) addition reduced weight loss significantly. The lowest weight loss was observed with M15 (2% steel fibre) among steel fibre-reinforced specimens (5.15% at 28 days). Likewise, nylon fibres (M16–M19) and glass fibres (M20–M23) also decreased weight loss, with M19 (2% nylon fibre) and M23 (2% glass fibre) recording the lowest at 4.75% and 6.77% respectively at 28 days.

4.4.2. Strength loss analysis

The loss in strength values reinforce the better performance of geopolymer concrete relative to ordinary concrete.

- Normal Concrete (M1) experienced the maximum loss in strength, with values of 20.70% at 28 days, dropping to 13.35% at 90 days.

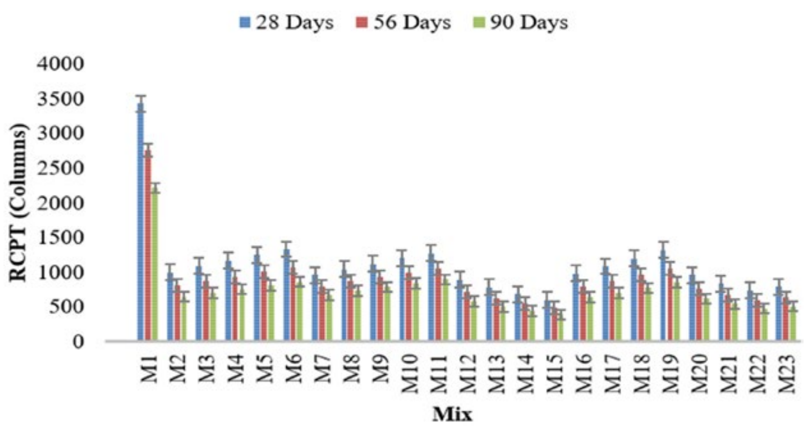

Figure 4: RCPT results.

- GGBS based Geopolymer Concrete (M2–M6, M7–M11) demonstrated excellent retention of strength. M6 (20% fly ash) registered the minimum loss of strength of 12.94% at 28 days.
- Influence of Curing Temperature: High-temperature curing (M7–M11) minimized loss of strength even more, with M11 recording the minimum at 12.42% at 28 days.
- Impact of Fibres: Addition of steel fibre increased strength retention very much. M15 (2% steel fibre) had the least percentage of strength loss (5.80% at 28 days). Nylon and glass fibres also helped in minimizing strength loss, with M19 (2% nylon fibre) and M23 (2% glass fibre) having the least percentages of 5.35% and 7.63%, respectively, at 28 days.

4.4.3. Comparison and discussion

- The findings suggest that geopolymer concrete is more resistant to saltwater exposure than traditional concrete.
- The incorporation of supplementary cementitious materials, especially GGBS, improves durability and minimizes degradation.
- Incorporating steel, nylon, and glass fibres enhances the mechanical efficiency and strength with steel fibres having the optimal effect in reducing weight and maintaining strength.
- Curing temperature is also critical, with high-temperature curing being beneficial for durability. Figure 5 and 6 illustrates percentage weight and strength loss in salt water resistance test results.

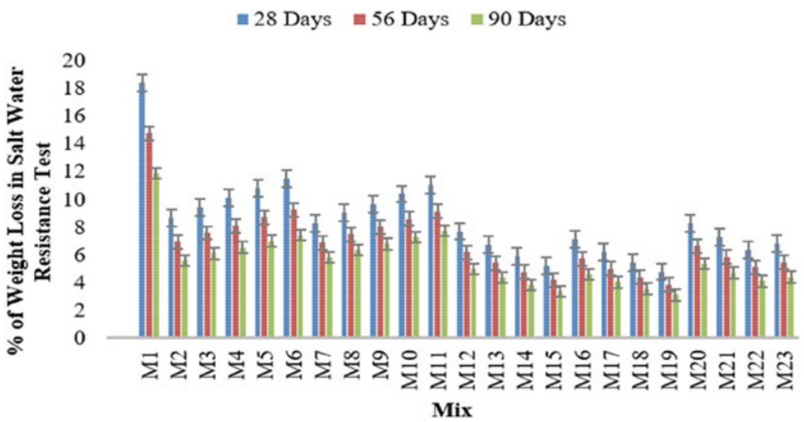

Figure 5: Percentage of weight loss in salt water resistance test results.

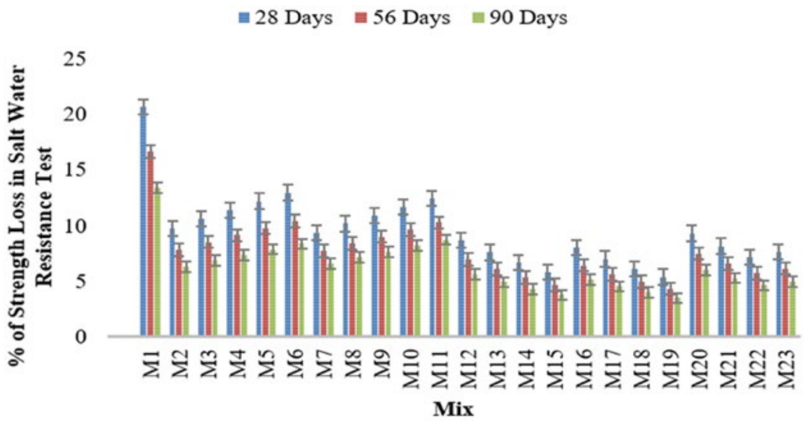

Figure 6: Percentage of strength loss in salt water resistance test results.

4.5. Sulphate attack test

4.5.1. Effect of curing mode on sulphate resistance

The results of the test show that geopolymer concrete (GPC) specimens have better sulphate resistance than normal concrete. All geopolymer mixes had a much lower weight loss percentage and strength loss compared to the control mix (M1). Also, GPC specimens cured at increased temperatures (60°C) indicated better sulphate resistance compared to specimens cured at room temperature.

M1 (normal concrete) had 19.14%, 15.37%, and 12.35% weight loss at 28, 56, and 90 days, respectively, while M7 (100% GGBS cured at 60°C) had much lower weight loss percentages of 8.63%, 7.13%, and 6.04% at the same ages. Likewise, strength loss for M1 was 21.58% at 28 days, while M7 had a lower value of 9.72%.

4.5.2. Effect of fly ash and GGBS content on sulphate resistance

The outcome is that a rise in percentage of fly ash and reduction in GGBS proportion results in the enhancement of sulphate-induced degradation. Mixes with 100% GGBS (M2 and M7) recorded the highest sulphate resistance with least weight and strength loss. Mixes having higher fly ash proportion (M3 to M6 and M8 to M11) recorded a step-by-step weight and strength loss.

For example, at 28 days, M2 had 8.99% weight loss, whereas M6 (20% fly ash) had a greater weight loss of 11.97%. Likewise, strength loss for M2 was 10.13%, whereas M6 had a greater loss of 13.49%. The trend holds true under various curing conditions, further supporting the positive contribution of GGBS to sulphate resistance.

4.5.3. Influence of steel fibre

The presence of steel fibres (M12 to M15) effectively enhanced sulphate resistance by minimizing weight and strength loss compared to fibreless GPC (M2). An increase in the proportion of steel fibres from 0.5% to 2% further increased resistance, with the least weight loss of 5.37% and strength loss of 6.05% at 28 days for M15.

4.5.4. Impact of nylon fibres

Like steel fibres, the use of nylon fibres (M16 to M19) had better sulphate resistance. Nylon fibres were weaker than steel fibres, however. M19 (2% nylon fibre) had 4.95% weight loss and 5.58% loss in strength at 28 days, which is lower compared to steel-fibre-reinforced GPC.

4.5.5. Influence of glass fibres

Glass fibre (M20 to M23) application also increased sulphate resistance but to a lesser degree than steel and nylon fibres. The optimum performance was found for M23 (2% glass fibre), which had 7.05% weight loss and 7.95% strength loss at 28 days.

4.5.6. Summary of key findings

- Geopolymer concrete had better resistance to sulphates than normal concrete.
- High temperature curing (60°C) enhanced sulphate resistance substantially.
- Greater percentage of GGBS caused reduced weight and strength loss.
- Addition of steel, nylon, and glass fibres further improved resistance to sulphates, the steel fibres exhibiting the highest improvement.

4.5.7. Conclusion

Geopolymer concrete proves to be much better in terms of performance under sulphate attack than normal concrete. Curing at 60°C, increased GGBS content, and fibre reinforcement can improve durability even more, hence GPC could be a practical option for use in structures in aggressive environments. Figure 7 and 8 indicates the weight loss percentage and strength loss in sulphate attack test results.

4.6. Sorptivity test

4.6.1. Effect of curing mode on sorptivity

Sorptivity of all mixtures reflects a marked effect of curing conditions. Conventional concrete (M1) showed the largest sorptivity values at every age, ranging from 5.77×10^{-5} m/s$^{1/2}$ at 28 days, 5.22×10^{-5} m/s$^{1/2}$ at 56 days, to 5.06×10^{-5} m/s$^{1/2}$ at 90 days. At curing using geopolymer concrete at room temperature (M2–M6), sorptivity

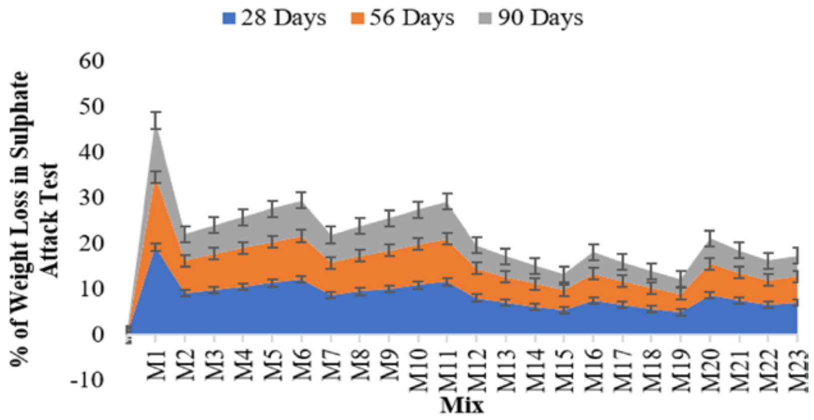

Figure 7: Percentage of weight loss in sulphate attack test results.

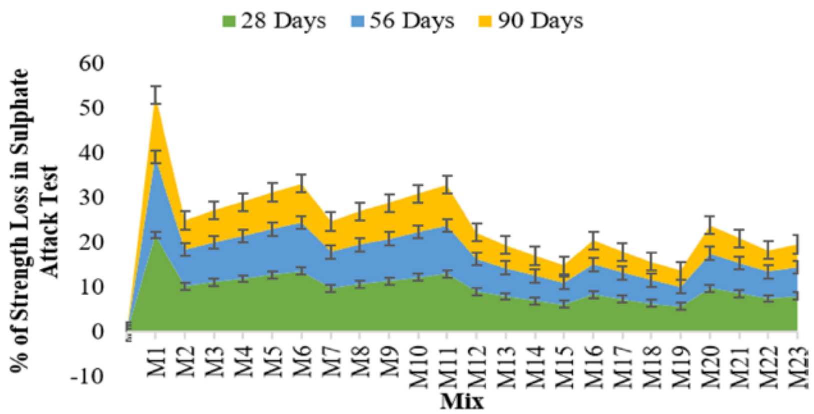

Figure 8: Percentage of strength loss in sulphate attack test results.

values decreased relative to conventional concrete. Healing at a higher temperature (60°C) (M7–M11) also had a positive effect on the performance, causing further decreases in sorptivity.

4.6.2. Fly ash and GGBS impact on sorptivity

The blending of fly ash and GGBS heavily impacted the sorptivity of geopolymer concrete. With a reduction in the percentage of GGBS from 100% (M2) to 80% (M6), sorptivity results increased. The pattern was the same for both room temperature and heat-curing samples. For example, M2 (100% GGBS, room temperature curing) contained a sorptivity of 4.60×10^{-5} m/s$^{1/2}$ at 28 days, while M6 (80% GGBS) contained 5.06×10^{-5} m/s$^{1/2}$. The same trend was found for heat-cured samples (M7–M11).

4.6.3. Effect of steel fibers on sorptivity

The addition of steel fibers in geopolymer concrete resulted in a significant reduction in sorptivity. As the proportion of steel fibers increased from 0.5% to 2% (M12–M15), the sorptivity values decreased progressively. At 90 days, M12 (0.5% steel fibers) had a sorptivity of 3.97×10^{-5} m/s$^{1/2}$, while M15 (2% steel fibers) had the lowest value of 3.70×10^{-5} m/s$^{1/2}$. The enhancement of matrix densification and crack-bridging action contributed by steel fibers is the reason for this improvement.

4.6.4. Impact of nylon fibers on sorptivity

The addition of nylon fibers (M16–M19) also reduced sorptivity, but less significantly than steel fibers. This is reflected in M16 (0.5% nylon fibers) with 3.99×10^{-5} m/s$^{1/2}$ and in M19 (2% nylon fibers) with 3.72×10^{-5} m/s$^{1/2}$ at 90 days. The decrease results from the capacity of nylon fibers to limit pore connectivity and enhance durability.

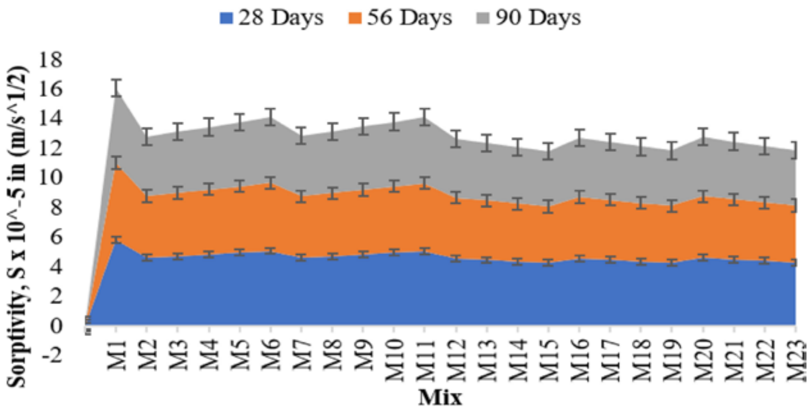

Figure 9: Sorptivity test results.

4.6.5. Effect of glass fibers on sorptivity

Similar to steel and nylon fibers, the inclusion of glass fibers (M20–M23) led to lower sorptivity values. The reduction was proportional to the fiber content, with M20 (0.5% glass fibers) showing a sorptivity of 4.01×10^{-5} m/s$^{1/2}$ at 90 days, while M23 (2% glass fibers) achieved a lower value of 3.73×10^{-5} m/s$^{1/2}$. The improvement in performance is due to the role of glass fibers in reducing capillary porosity and enhancing matrix integrity.

4.6.6. Comparative performance analysis

Of all the mixtures, M15 (2% steel fibers) had the minimum sorptivity values at all curing ages. The comparative study indicates that the fiber-reinforced geopolymer concretes were better than the plain ones, and among the fibers, steel fibers provided the greatest reduction in sorptivity, followed by glass and nylon fibers. Heat curing also increased the resistance to water absorption more than room temperature curing.

4.6.7. Conclusion

The research supports that geopolymer concrete has lower sorptivity than normal concrete, and the impact is further increased by fiber reinforcement, GGBS content, and curing temperature. Steel fibers among the tested fibers had the highest sorptivity reduction, and they are a good option for enhancing the durability of geopolymer concrete. Heat curing was also found to be helpful in curbing the water absorption, and it is a good method for improving long-term performance. Figure 9 shows the sorptivity test results.

5. CONCLUSION

This study examined the mechanical and durability performance of geopolymer concrete (GPC) formulated with varying ratios of fly ash and ground granulated blast furnace slag (GGBS), reinforced with different types of fibers. The results demonstrate that binder composition and fiber type are interdependent factors that significantly influence both strength development and resistance to environmental degradation.

The mix designated as M15—containing 100% GGBS and 2% steel fibers—exhibited the best overall performance. It achieved very low RCPT values (383 Coulombs), indicating high resistance to chloride ion penetration. Furthermore, M15 recorded the lowest mass losses in acid (3.06%) and saltwater (3.32%) exposure tests, along with the lowest sorptivity (3.70×10^{-5} m/s$^{1/2}$), reflecting reduced permeability. These results suggest a dense and durable matrix, likely due to the formation of C–A–S–H gel in GGBS-rich systems, coupled with enhanced crack-bridging and interfacial bonding provided by steel fibers.

While other fiber-reinforced mixes such as M19 (2% nylon fibers) and M23 (2% glass fibers) demonstrated moderate improvements in durability, they fell short of the performance achieved by steel fiber reinforcement. The superior performance of steel fibers can be attributed to their stiffness and ability to improve microcrack control, especially under aggressive exposure conditions.

The high reactivity of GGBS contributed significantly to early strength and microstructural refinement through the generation of C–A–S–H gel, which also reduced porosity and improved chemical resistance. In contrast, fly ash-rich blends, though more chemically stable due to N–A–S–H gel formation, exhibited higher permeability and lower mechanical performance under the tested conditions.

The GPC mix based on 100% GGBS with 2% steel fibers represents a viable, durable, and sustainable alternative to conventional concrete. It leverages both chemical and physical reinforcement mechanisms to resist degradation. Future research should explore hybrid fiber systems, long-term performance in real-world environments, and the use of alternative activators or nano-modified precursors to further optimize geopolymer concrete for infrastructure applications. Future research extended studies on carbonation, chloride penetration, freeze–thaw resistance, and alkali–silica reaction (ASR) are essential to validate the material's performance in aggressive environments over service lifespans. Comprehensive life cycle analysis (LCA) and embodied carbon benchmarking compared to OPC (Ordinary Portland Cement) concrete will help position geopolymer systems within sustainable construction policies.

6. BIBLIOGRAPHY

[1] AL-MAJIDI, M., LAMPROPOULOS, A., CUNDY, A., "Steel fibre reinforced geopolymer concrete (SFRGC) with improved microstructure and enhanced fibre-matrix interfacial properties", *Construction & Building Materials*, v. 139, pp. 286–307, 2017. doi: http://doi.org/10.1016/j.conbuildmat.2017.02.045.

[2] BOUAISSI, A., LI, L., AL BAKRI ABDULLAH, M.M., *et al.*, "Mechanical properties and microstructure analysis of FA-GGBS-HMNS based geopolymer concrete", *Construction & Building Materials*, v. 210, pp. 198–209, 2019. doi: http://doi.org/10.1016/j.conbuildmat.2019.03.202.

[3] BELLUM, R.R., "Influence of steel and PP fibers on mechanical and microstructural properties of fly ash-GGBFS based geopolymer composites", *Ceramics International*, v. 48, n. 5, pp. 6808–6818, 2021. doi: http://doi.org/10.1016/j.ceramint.2021.11.232.

[4] GANESH, A., MUTHUKANNAN, M., "Development of high performance sustainable optimized fiber reinforced geopolymer concrete and prediction of compressive strength", *Journal of Cleaner Production*, v. 282, pp. 124543, 2020. doi: http://doi.org/10.1016/j.jclepro.2020.124543.

[5] XU, Z., ZHANG, J., ZHANG, J., *et al.*, "Influence of steel slag and steel fiber on the mechanical properties, durability, and life cycle assessment of ultra-high performance geopolymer concrete", *Construction & Building Materials*, v. 441, pp. 137590, 2024. doi: http://doi.org/10.1016/j.conbuildmat.2024.137590.

[6] XU, S., YUAN, P., LIU, J., *et al.*, "Development and preliminary mix design of ultra-high-performance concrete based on geopolymer", *Construction & Building Materials*, v. 308, pp. 125110, 2021. doi: http://doi.org/10.1016/j.conbuildmat.2021.125110.

[7] ZHAO, Q., WANG, Y., XIE, M.-Q., *et al.*, "Experimental study on mechanical behavior of steel fiber reinforced geopolymeric recycled aggregate concrete", *Construction & Building Materials*, v. 356, pp. 129267, 2022. doi: http://doi.org/10.1016/j.conbuildmat.2022.129267.

[8] RAZA, A., AHMED, B., EL OUNI, M.H.E., *et al.*, "Mechanical, durability and microstructural characterization of cost-effective polyethylene fiber-reinforced geopolymer concrete", *Construction & Building Materials*, v. 432, pp. 136661, 2024. doi: http://doi.org/10.1016/j.conbuildmat.2024.136661.

[9] PRUSTY, J.K., PRADHAN, B., "Evaluation of durability and microstructure evolution of chloride added fly ash and fly ash-GGBS based geopolymer concrete", *Construction & Building Materials*, v. 401, pp. 132925, 2023. doi: http://doi.org/10.1016/j.conbuildmat.2023.132925.

[10] LI, W., SHUMUYE, E.D., SHIYING, T., *et al.*, "Eco-friendly fibre reinforced geopolymer concrete: A critical review on the microstructure and long-term durability properties", *Case Studies in Construction Materials*, v. 16, pp. e00894, 2022. doi: http://doi.org/10.1016/j.cscm.2022.e00894.

[11] ABBAS, A.-G.N., AZIZ, F.N.A.A., ABDAN, K., *et al.*, "Experimental study on durability properties of kenaf fibre-reinforced geopolymer concrete", *Construction & Building Materials*, v. 396, pp. 132160, 2023. doi: http://doi.org/10.1016/j.conbuildmat.2023.132160.

[12] YAVANA RANI, S., SALEH NUSARI, M., BIN NON, J., *et al.*, "Durability of geopolymer concrete with addition of polypropylene fibre.", *Materials Today: Proceedings*, v. 56, pp. 2846–2851, 2022. doi: http://doi.org/10.1016/j.matpr.2021.10.164.

[13] WASIM, M., NGO, T.D., LAW, D., "A state-of-the-art review on the durability of geopolymer concrete for sustainable structures and infrastructure", *Construction & Building Materials*, v. 291, pp. 123381, 2021. doi: http://doi.org/10.1016/j.conbuildmat.2021.123381.

[14] SATHISH KUMAR, V., GANESAN, N., INDIRA, P.V., "Effect of hybrid fibres on the durability characteristics of ternary blend geopolymer concrete", *Journal of Composites Science*, v. 5, n. 10, pp. 279, 2021. doi: http://doi.org/10.3390/jcs5100279.

[15] LAXMI, G., PATIL, S., HOSSINEY, N., *et al.*, "Effect of hooked end steel fibers on strength and durability properties of ambient cured geopolymer concrete", *Case Studies in Construction Materials*, v. 18, pp. e02122, 2023. doi: http://doi.org/10.1016/j.cscm.2023.e02122.

[16] ANBARASU, N.A., SIVAKUMAR, V., YUVARAJ, S., *et al.*, "Pioneering the next frontier in construction with high-strength concrete infused by nano materials", *Matéria*, v. 30, pp. e20240730, 2025. doi: http://doi.org/10.1590/1517-7076-rmat-2024-0730.

[17] SIKDER, A., MISHRA, J., KRISHNA, R.S., *et al.*, "Evaluation of the mechanical and durability properties of geopolymer concrete prepared with C-glass fibers", *Arabian Journal for Science and Engineering*, v. 48, n. 10, pp. 12759–12774, 2023. doi: http://doi.org/10.1007/s13369-022-07558-y.

[18] ALEXANDER, A.E., SHASHIKALA, A.P., "Studies on the mechanical and durability performance of textile reinforced geopolymer concrete beams", *Materials Today. Communications*, v. 35, pp. 105837, 2023. doi: http://doi.org/10.1016/j.mtcomm.2023.105837.

[19] CHEN, C., ZHANG, X., HAO, H., "Dynamic tensile properties of geopolymer concrete and fibre reinforced geopolymer concrete", *Construction & Building Materials*, v. 393, pp. 132159, 2023. doi: http://doi.org/10.1016/j.conbuildmat.2023.132159.

[20] MURTHY, S.S., PATIL, N.N., "Mechanical and durability characteristics of flyash and GGBFS based polypropylene fibre reinforced geopolymer concrete", *Materials Today: Proceedings*, v. 59, pp. 18–24, 2022. doi: http://doi.org/10.1016/j.matpr.2021.10.036.

[21] ANVARI, M.A., TOUFIGH, V., "Experimental and probabilistic investigation on the durability of geopolymer concrete confined with fiber reinforced polymer.", *Construction & Building Materials*, v. 334, pp. 127419, 2022. doi: http://doi.org/10.1016/j.conbuildmat.2022.127419.

[22] MOHAMED, O.A., "Effect of immersing geopolymer slag-fly ash mortar in sulfuric acid on strength development and stability of mass", *Construction & Building Materials*, v. 341, pp. 127786, 2022. doi: http://doi.org/10.1016/j.conbuildmat.2022.127786.

[23] MOHAMED, O.A., "Effects of the curing regime, acid exposure, alkaline activator dosage, and precursor content on the strength development of mortar with alkali-activated slag and fly ash binder: a critical review", *Polymers*, v. 15, n. 5, pp. 1248, 2023. doi: http://doi.org/10.3390/polym15051248. PubMed PMID: 36904489.

[24] ANBARASU, N.A., KESHAV, L., RAJA, K.C.P., *et al.*, "Unraveling the flexural behavior of concrete and compare with innovative fea investigations", *Matéria*, v. 29, n. 4, pp. e20240656, 2024. doi: http://doi.org/10.1590/1517-7076-rmat-2024-0656.

[25] VISWANATHAN, K.E., KRISHNARAJA, A.R., SUBRAMANIAM, A., *et al.*, "Flexural performance of reinforced concrete beam with layer of hybrid strain-hardening cementitious composites", *Matéria*, v. 30, pp. e20240697, 2025. doi: http://doi.org/10.1590/1517-7076-rmat-2024-0697.

[26] VIJAYA PRASAD, B.; ANAND, N.; KANAGARAJ, B., *et al.*, "Investigation on residual bond strength and microstructure characteristics of fiber-reinforced geopolymer concrete at elevated temperature", *Case Studies in Construction Materials*, v. 19, pp. e02526, 2023. doi: http://doi.org/10.1016/j.cscm.2023.e02526.

[27] SHANKAR, S., "Exploring the strength and durability characteristics of high-performance fibre reinforced concrete containing nanosilica", *Journal of the Balkan Tribological Association*, v. 30, n. 1, 2024.

[28] ARUNKUMAR, K., MUTHUKANNAN, M., SURESHKUMAR, A., *et al.*, "Mechanical and durability characterization of hybrid fibre reinforced green geopolymer concrete", *Research on Engineering Structures and Materials*, v. 8, n. 1, pp. 19–43, 2022.

[29] DHASMANA, A., SINGH, S.P., "Long-term mechanical characteristics of fibre reinforced metakaolin-based geopolymer concrete: a review", *Materials Today: Proceedings*, v. 93, pp. 106–119, 2023. doi: http://doi.org/10.1016/j.matpr.2023.07.030.

[30] ZUAITER, M., EL-HASSAN, H., EL-MAADDAWY, T., *et al.*, "Properties of slag-fly ash blended geopolymer concrete reinforced with hybrid glass fibers", *Buildings*, v. 12, n. 8, pp. 1114, 2022. doi: http://doi.org/10.3390/buildings12081114.

[31] YANG, S., ZHAO, R., MA, B., *et al.*, "Mechanical and fracture properties of fly ash-based geopolymer concrete with different fibers", *Journal of Building Engineering*, v. 63, pp. 105281, 2023. doi: http://doi.org/10.1016/j.jobe.2022.105281.

[32] BARIŞ, K.E., TANAÇAN, L., "Natural pozzolan-based green geopolymer foam for thermal insulation", *Journal of Sustainable Construction Materials and Technologies*, v. 7, n. 3, pp. 128–144, 2022. doi: http://doi.org/10.47481/jscmt.1142100.

[33] RAO, B., DURGA, C.S.S., VENKATESH, C., *et al.*, "Sustainable geopolymer concrete for pavements: Performance evaluation of recycled concrete aggregates in fly ash-based mixtures", *Journal of Sustainable Construction Materials and Technologies*, v. 9, n. 3, pp. 211–220, 2024. doi: http://doi.org/10.47481/jscmt.1554284.

[34] GEZER, T., AKARKEN, G., CENGIZ, U., "Production and characterization of heat retardant fiber-reinforced geopolymer plates", *Journal of Sustainable Construction Materials and Technologies*, v. 7, n. 4, pp. 282–290, 2022. doi: http://doi.org/10.47481/jscmt.1197471.

[35] TAMMAM, Y., UYSAL, M., CANPOLAT, O., *et al.*, "Effect of waste filler materials and recycled waste aggregates on the production of geopolymer composites", *Arabian Journal for Science and Engineering*, v. 48, n. 4, pp. 4823–4840, 2023. doi: http://doi.org/10.1007/s13369-022-07230-5.

[36] DURGA, C.S.S., CHAVA, V., PRIYANKA, M., *et al.*, "Synergistic effects of GGBFS addition and oven drying on the physical and mechanical properties of fly ash-based geopolymer aggregates", *Journal of Sustainable Construction Materials and Technologies*, v. 9, n. 2, pp. 93–105, 2021. doi: http://doi.org/10.47481/jscmt.1501001.